Project EEMS026
CAVs Pillar

U.S. DEPARTMENT OF ENERGY
SMARTMOBILITY
Systems and Modeling for Accelerated Research in Transportation

Expanding Regional Simulations of Connected and Automated Vehicles (CAVs) to the National Level and Assessing Uncertainties

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2019 Vehicle Technologies Office Annual Merit Review
June 11, 2019

Argonne NATIONAL LABORATORY
INL Idaho National Laboratory
BERKELEY LAB
OAK RIDGE National Laboratory
NREL NATIONAL RENEWABLE ENERGY LABORATORY

Overview

Timeline

Project start: 1 Oct 2016

Project end: 30 Sep 2019

Percent completed: 80%

Barriers

- Computational difficulty of accurately modeling and simulating large- scale transportation systems
- Accurately measuring the transportation system-wide energy impacts of connected and automated vehicles
- Complex role of the human decision-making process in mobility systems

Budget

FY 2017: $421k

FY 2018: $760k

FY 2019: $300k

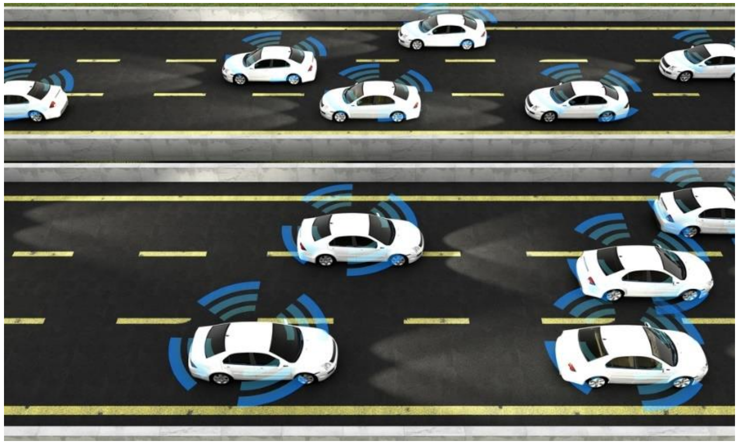
(100% DOE)

Partners

- Interactions / Collaborations
  - Oak Ridge National Laboratory
  - National Renewable Energy Laboratory
  - University of Illinois at Chicago
  - University of Maine
- Project lead: T. Stephens, Argonne

Objective

- **Estimate potential energy and mobility impacts of connected and automated vehicles (CAVs) at a national (U.S.) level**
  - Develop methods to estimate potential CAVs technology adoption rates
  - Develop methods to aggregate detailed results of case studies to the national level
  - Develop response-surface/reduced form methods to give technical/behavioral outcomes at regional/national level
  - Apply methods and deliver estimates of national level energy and mobility impacts of CAVs



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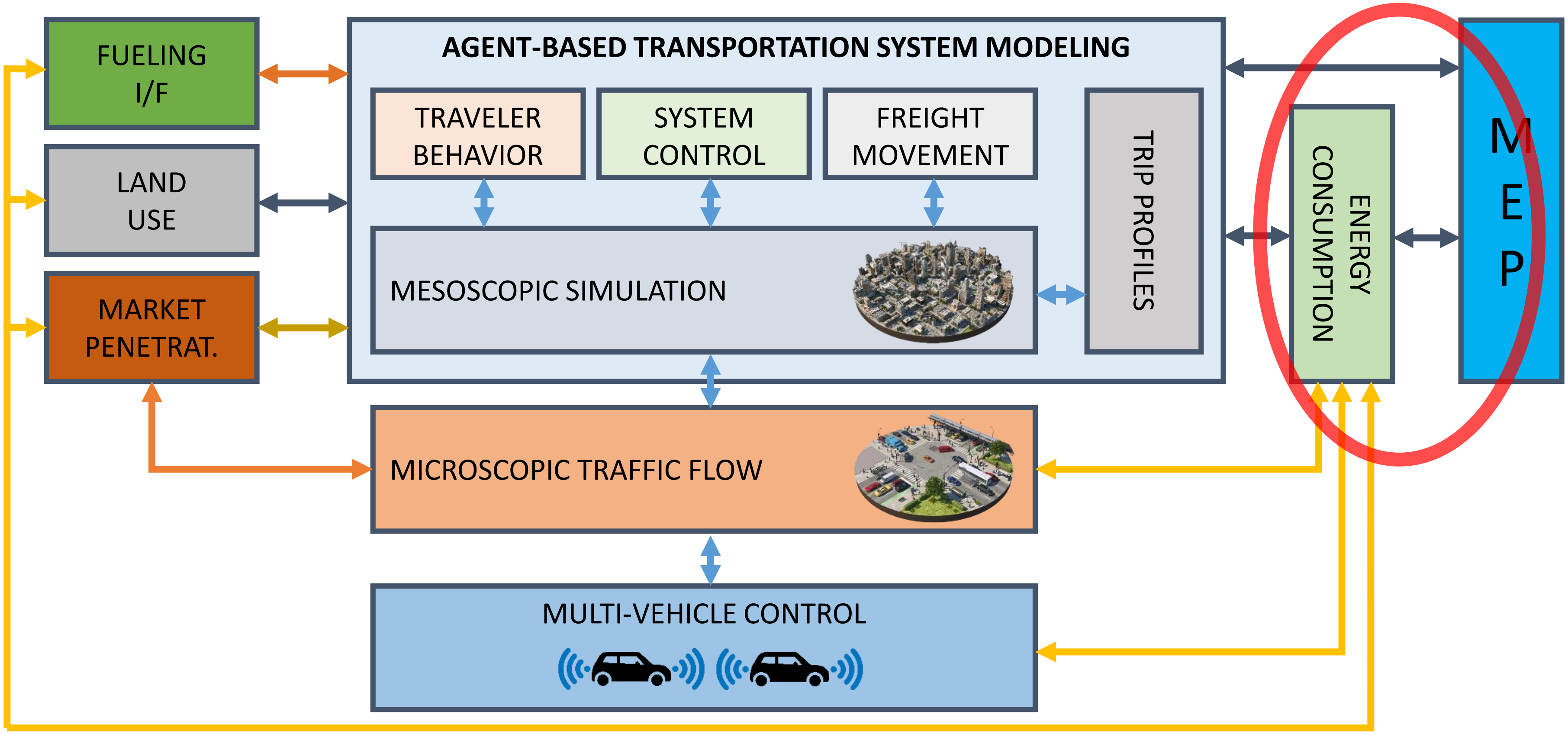
Milestones

Month/year	Description	Status
Jun 2018	Preliminary design of HDV & shared mobility model components	Complete
Jun 2018	Report on CAV market penetration scenario analysis	Complete
Sep 2019	Model implementation and runs including multiyear dynamics and new components for LDVs	On track
Sep 2019	National-level energy impact estimates for CACC plus 1-2 additional CAVs technologies (pending data availability) under different conditions (adoption levels, value of travel time, etc.)	Deleted
Jun 2019	Delivered publishable CAV market penetration scenarios results using MA3T-MC	On track
Sep 2019	Finalize CAVESIM model and analysis for full set of cases mapping aggregate national outcomes, compare with SMART/Meso-scale modeling results	On track

This Task Delivers National-level Energy, Mobility, and Cost Results, Based on Output of Other Tasks

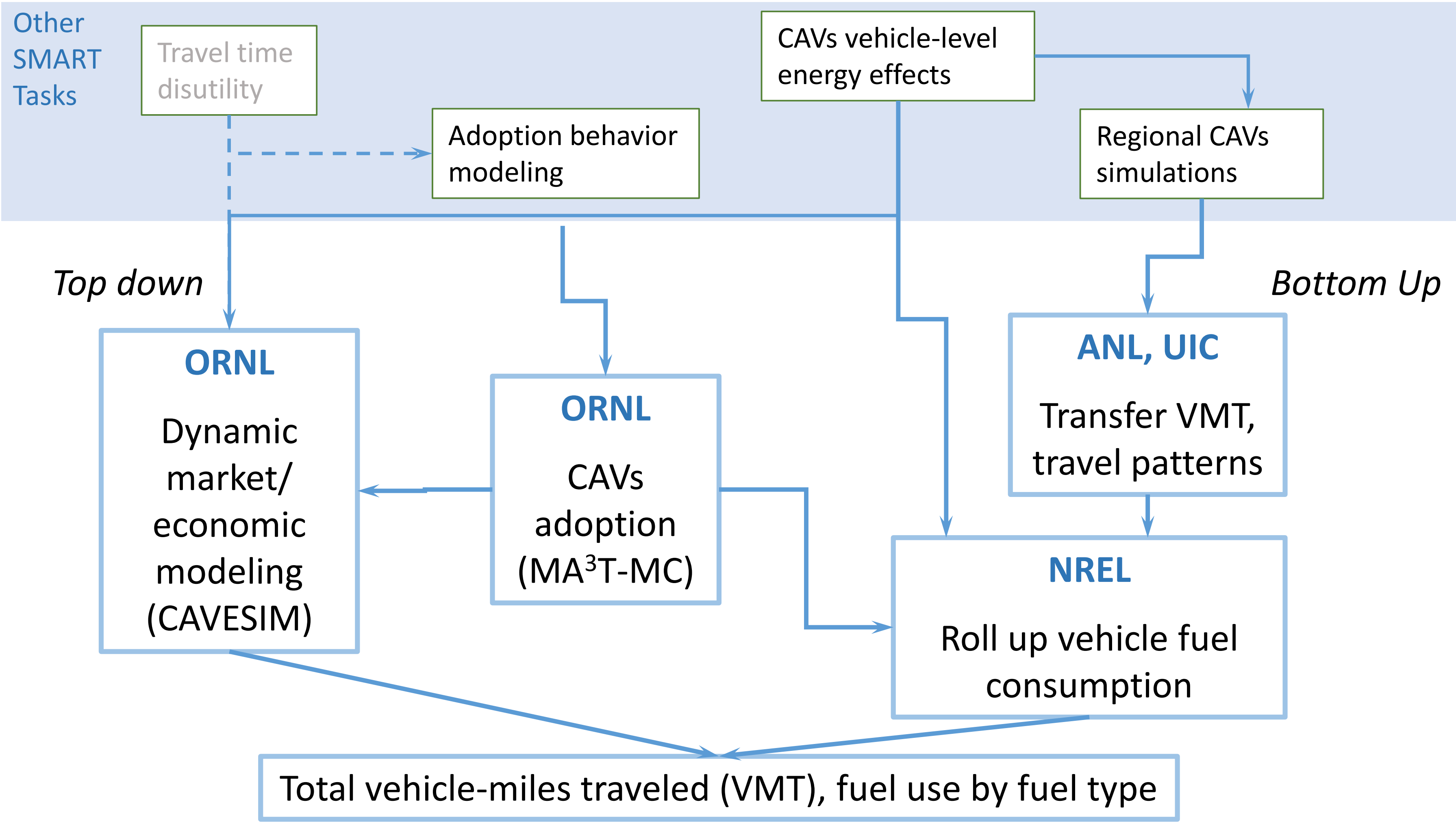
END-TO-END MODELING WORKFLOW



Addressing the Gaps: Approach

- Review CAVs energy/mobility literature and identify key knowledge gaps (see EEMS 081 poster)
- Two approaches to national-level analysis:
  - Top-down:
    - Use economic (producer/consumer behavior) modeling to estimate demand
    - Determine energy/travel effects from summary representation of results & response functions from larger, disaggregated spatial models
  - Bottom-up:
    - Estimate potential adoption/utilization of CAVs by different user groups
    - Take detailed results from simulations of travelers and vehicles and expand to a national level
- Cases
  - Cooperative adaptive cruise control (CACC)
  - Highly automated passenger vehicles (private/shared)

Overall Task Structure and Interactions with Other Tasks



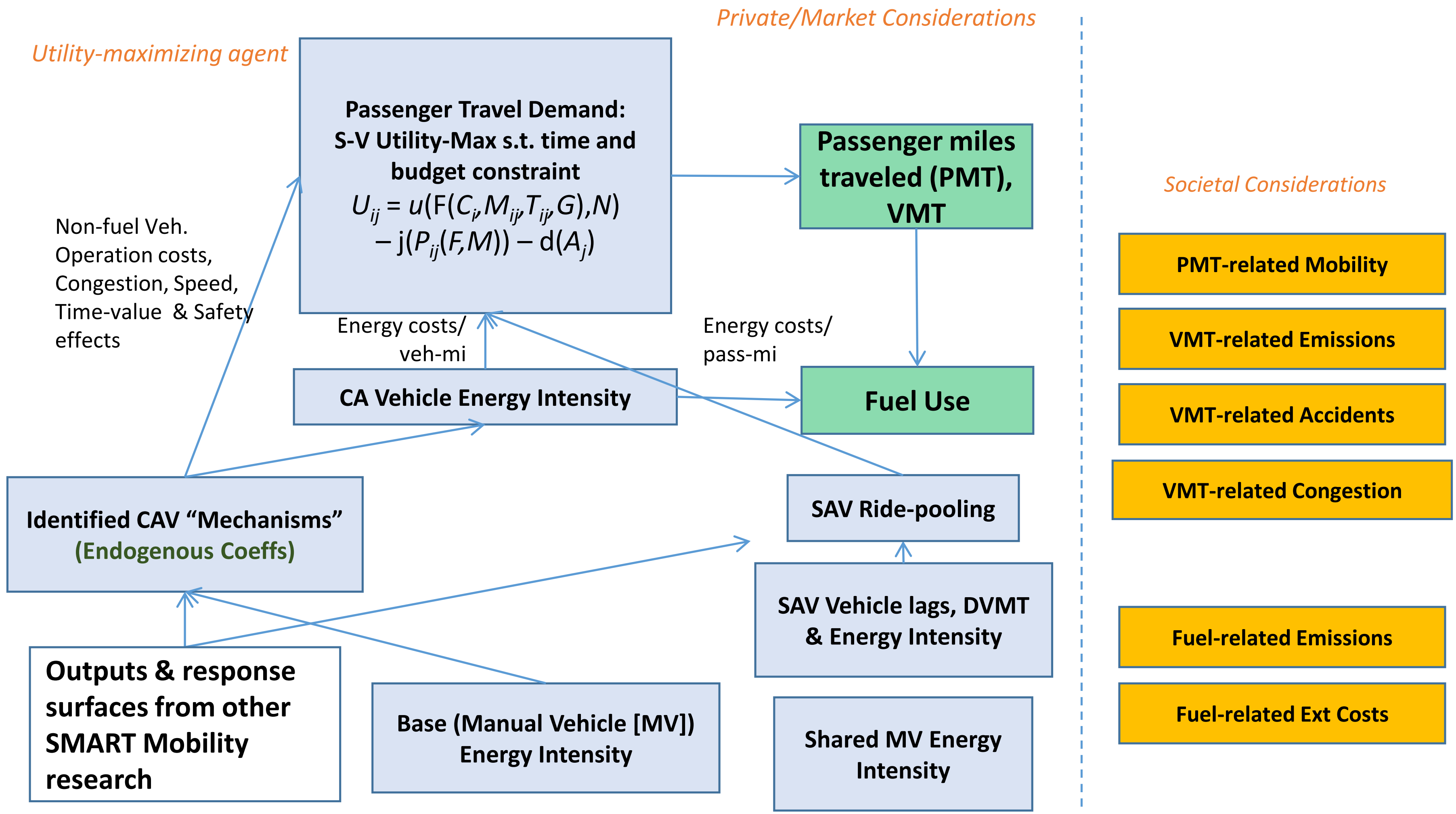
CAVESIM Top-Down Approach

- **Goal:** Produce insights and response information at national level
  - VMT, energy as function of cost/time-value/income/budget
- Model produces estimates of **national** (or regional) changes in VMT, fuel use
- Much more aggregated, but more nimble than flagship regional meso-scale agent-based modeling
- Founded in economic theory, emphasizes importance of cost economics for outcomes
- Representative travelers behave according to constrained utility (preference) max

CAVESIM Connections

- **Connections to SMART Workflow (data and assumptions)**
  - Employ common base Scenario assumption set
  - Benchmark to POLARIS and BEAM results/behaviors
  - IDed detailed list of inputs to use from other SMART studies
- **Connections to other subtasks in this project**
  - Use Vehicle Tech Penetration cases from MA^{3}T-MC
    - and offer relations for use by MA^{3}T-MC
  - Contribute to updated Bounds report on National Energy and Mobility Impacts of CAVs (EEMS081)
- **Aggregate outputs can provide**: comparison, mobility benefits measures (energy, travel, economic), additional cases

CAVESIM Top-Down Conceptual Approach Complements Bottom-up National Aggregation and Detailed Regional Analyses



National-level impacts (Top-down), Formulation

- **Use economic (producer/consumer behavior) modeling to estimate demand, efficiency, ride sharing, congestion, energy use [other outcomes?]**
- **Utility-maximizing agent**
  - **Utility, *Uij*, depends on costs (vehicle, fuel, time)**
  - **Social costs also considered (emissions, congestion, accidents)**
  - **Analytic form allows exploring ranges of imposed costs with constraints under different combinations of inputs to find combinations producing maximum benefit**

$$U_{ij} = u(\psi(C_i, M_{ij}, T_{ij}, G), N) - \phi(P_{ij}(F_i, M_{ij}) - \delta(A_i)$$

i: AV or MV
j: urban or non-urban

C_i, quantity of goods consumed
M_{ij}, vehicle-miles traveled
T_{ij}, time spent driving
G, government spending
N, leisure
P_{ij}, quantity of pollution

A_i, severity-adjusted traffic accidents
L, labor supply
$I = (1 - t_L)L$, after-tax income
F_i, fuel consumption
P_F, fuel price, including taxes
H_i, vehicle and other driving costs

CAVESIM Conceptual Approach: Main Potential Impacts of Connectivity/ Automation Represented, Estimated, and Interacted

1. **Summarize Effects on Vehicle Energy Intensity**
   - ~8 Identified technological mechanisms
2. **Summarize/Estimate Effects on Costs, Travel "Costs"**
   - Vehicle capital and operating costs, (including energy)
   - Time costs: Value of travel time per hr (VoTT/hr) and speed, congestion
3. **Estimate Effects on Road Travel Demand** (VMT, PMT)
   - Shifts in Demand (apart from cost response)
     - New/underserved rider groups
     - Ride-hailing/Ride-pooling
     - *Mode shifts (from transit, rail/bus, air)*
   - Total Demand (PMT) response to Δcost/convenience
4. **Model interactive/equilibrating effects** among (some) energy intensity, costs, and demand impacts

CAVESIM High-level Inputs/Assumptions and Outputs

- Summarize technological and operational "mechanisms" by which CAVs alter energy use
  - CACC/Platooning
  - Eco-driving
  - Congestion mitigation (incl. Traffic-flow control)
  - Altered highway speeds
  - De-emphasized performance
  - Improved crash avoidance (light-weighting)
  - Increased feature load (incl. sensors/controls)
  - Vehicle size & "Right-sizing"
  - "Ride hailing"/"Ride pooling"
  - *Electrification*
  - Demand from New user groups
  - Demand response *(mode shifts/induced demand)*
- Establish estimated base energy intensity and demand impacts for mechanisms
  - At different levels of CAV penetration
- Summarize known cost information, effect of technologies and pooling on vehicle and passenger costs
- Summarize Key Response relationships (Demand response, VoTT, speed/congestion effects)
- Account for equilibrium interactions (through costs/benefits): demand, congestion, speed, safety energy-intensity, & cost
- Define and Model alternative scenarios: (defines exogenous assumptions and endogenous)
- **Explore implications of alternative conditions/costs on outcomes**

Expanding Regional Travel Changes to National Level Requires Alternate Approach

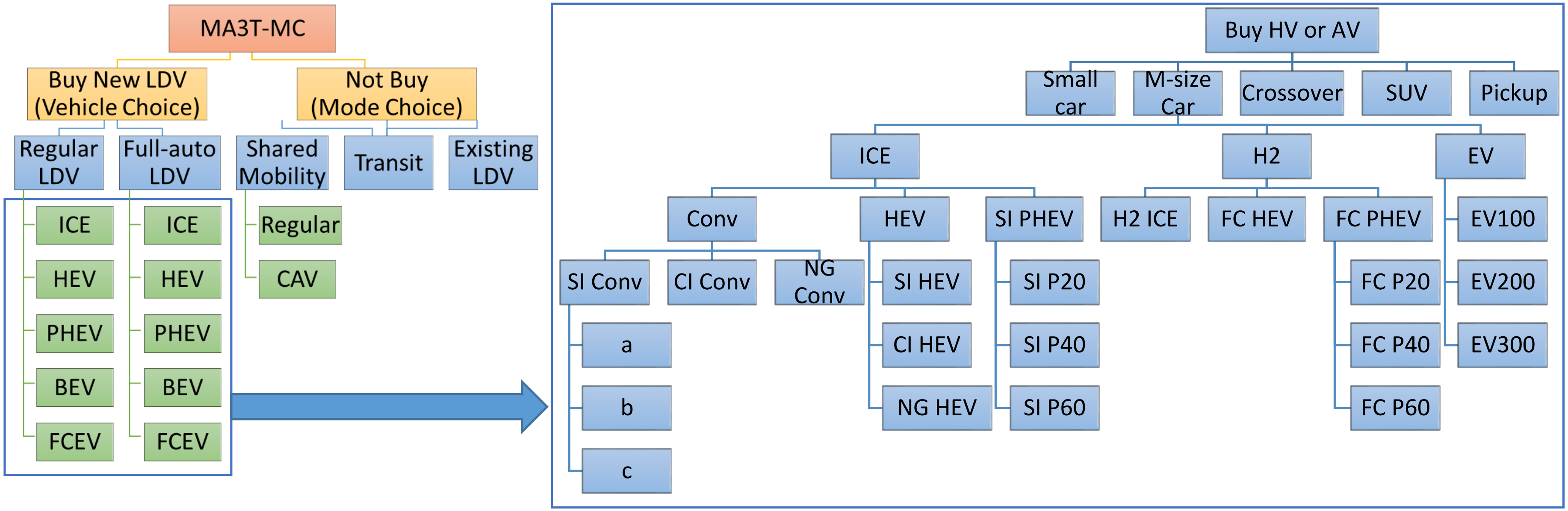
Initial Approach: Transfer vehicle miles traveled (VMT) to national level

Alternate approach: Model changes in traffic flows by road link type

- Comparing traffic flows, average daily traffic flows (ADT) by road link
- Develop models for the change in ADT in terms of variables characterizing the link, local network. and land use
- Two approaches, analyzing changes due to (CACC):
  - Model difference in ADT: (CACC – No CACC)
  - Model percent change in ADT: (CACC – No CACC) / CACC
- Explanatory variables
  - Characteristics of census block groups along links
  - Link characteristics:
    - Distance to central business district
    - Connectivity
    - Type: Freeway, Expressway, Minor, Collector
    - Surrounding land use (weighted average along the link)

MA3T-MC: Nested multinomial logit theory with relevant vehicle and mobility technologies

- Considers diverse technologies, consumer heterogeneity, induced travel demand, and systems dynamics
- Built on the VTO-funded fuel technology choice model MA^{3}T
- Calibrated with or linked to TEDB, NHTS 2017, WholeTraveler, American Housing Survey, POLARIS, Autonomie, FastSIM



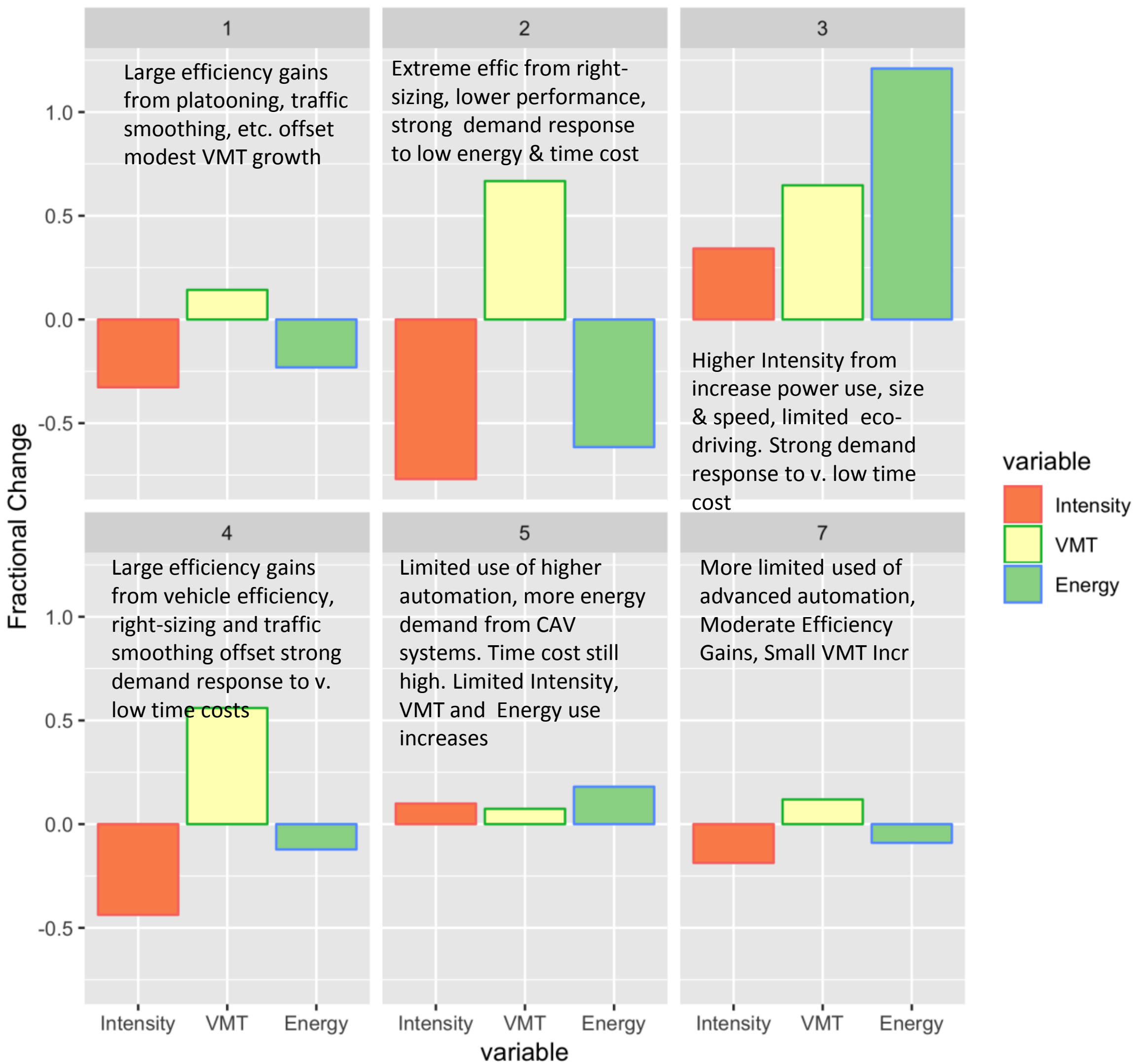
CAVESIM Results to Date

- Implementation of CAVSIM version with LDVs, simple HDV representation
- Performed sensitivity analysis on decentralized incentives, alternative costs (slides 17 & 30)
- Completed draft formulation of CAV VMT and energy impacts with Pooling (slide 18, 19)
- Developed, now testing, versions with Shared/pooled TNC rides
  - Viewed as critical for cost of AV travel and VMT impacts
- Benchmarking to SMART Mobility “work/data flow”
  - Scenario assumptions
  - Results/insights from micro and meso-scale model runs

Results: Exploring Demand and VMT for Wide Range of Demand and Technology Scenarios. Now being Benchmarked

Fig: Energy-Intensity, VMT, and Energy Scenarios

LDV CAVs, Excludes Pooling/Sharing

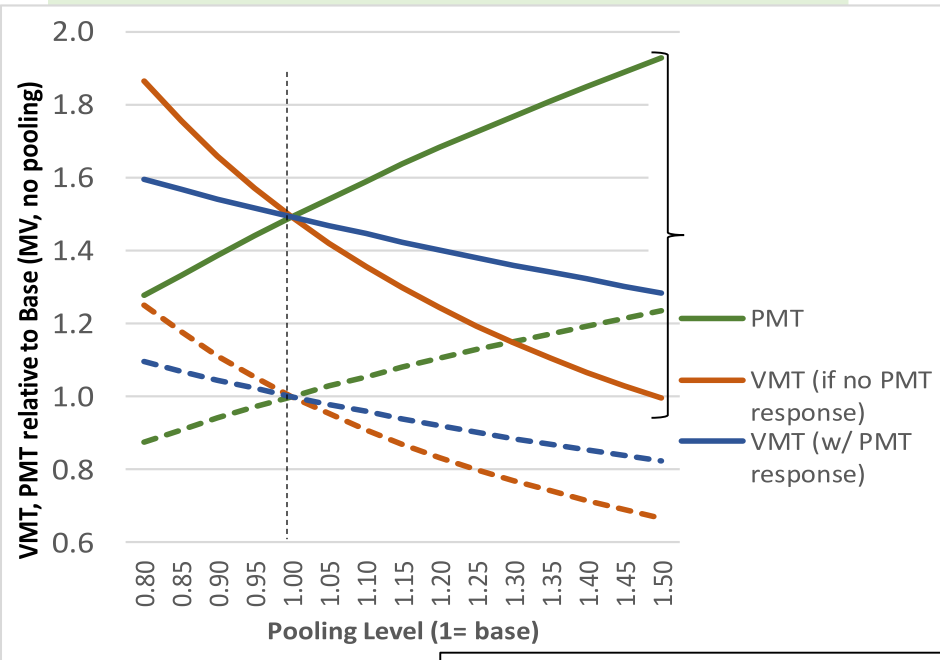


- Energy "intensity" is fuel use/vehicle-mile.
- Fractional changes in vehicle energy intensity, VMT, and energy use from base (all MV) case
- Results depend strongly on
  - Alternative technology outcomes,
  - Full travel-cost implications, and
  - Traveler responsiveness to AV convenience and cost.

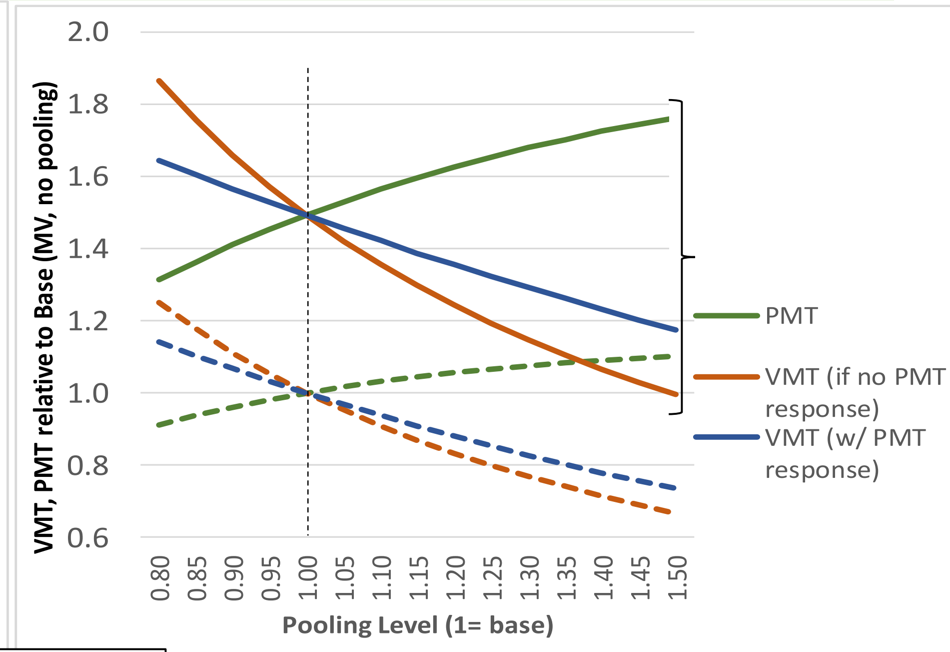
Accounting for Vehicle Sharing (Pooling) alters Economic Costs, Time Cost, and Travel Demand Responses

- **VMT, PMT and Energy at No-Pooling/Sharing point (Pooling=1.0) determined from net effect of energy intensity mechanisms, costs changes, and demand response (Base is no pooling, MV).**
- **Increased Pooling Enables Higher PMT and Lower VMT**
- **But VMT demand responds to economics of lower costs, possible time-cost penalty**

Pooling with Operational cost savings/sharing, No Time Cost Penalty



Increasing Time Cost Penalty with Pooling



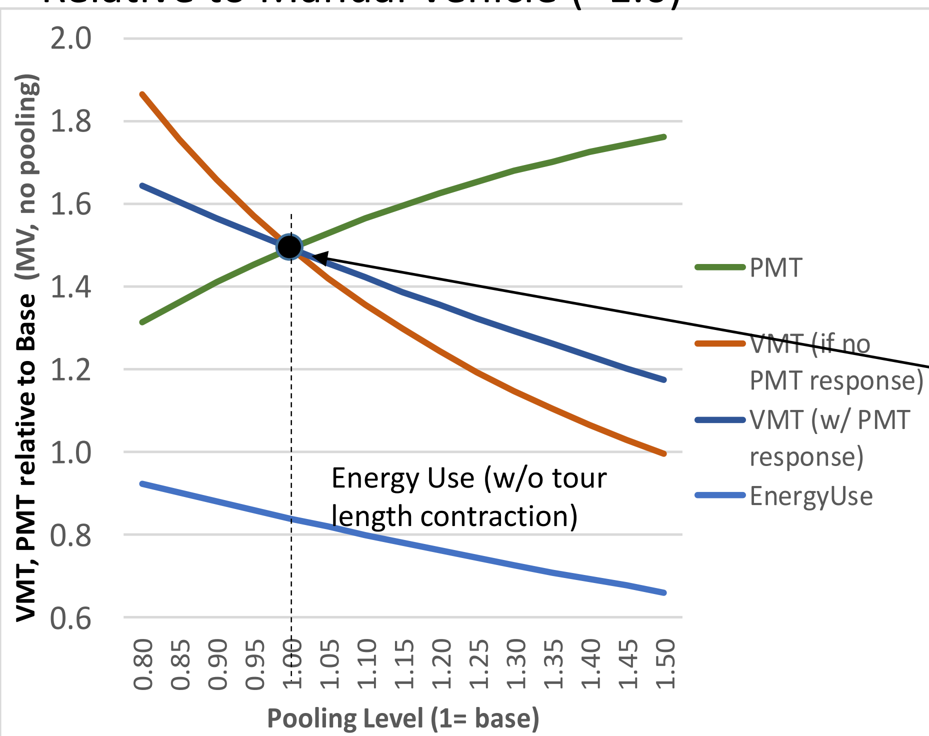
Pooling level < reflects deadheading/ repositioning miles for an AV and for a shared MV like Uber/.Lyft (both zero passenger occupancy). Driver of Shared TNC vehicle is not counted.

Solid curves: CAV outcomes;
Dotted curves: MV outcomes.

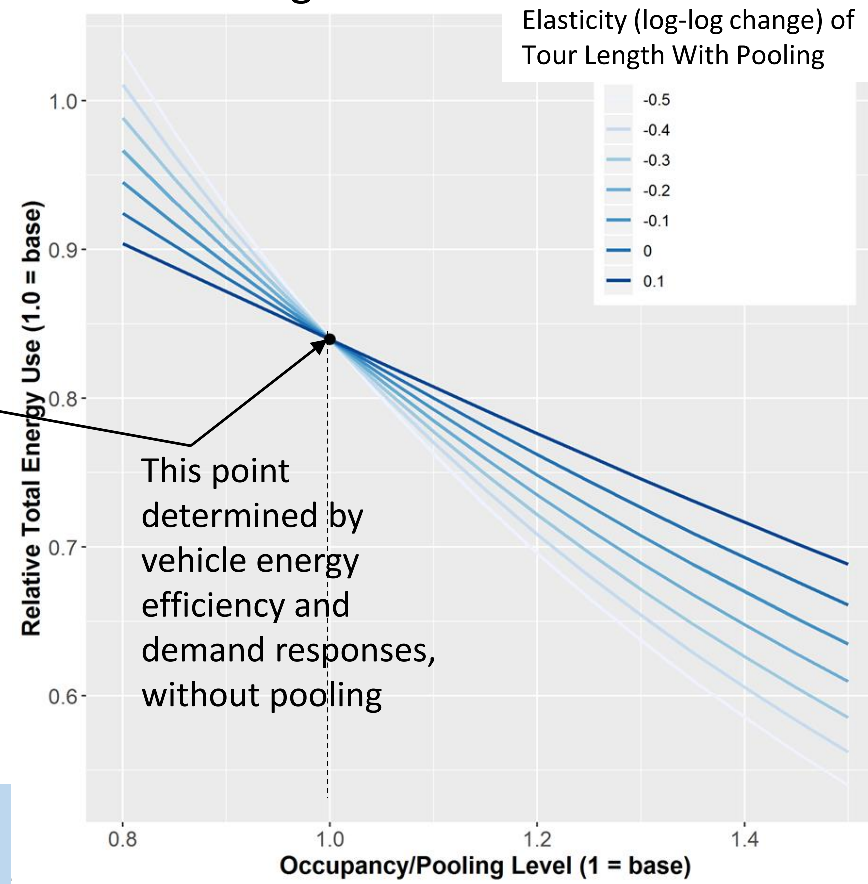
Energy Use Depends on Extent of Ride Pooling, and Route (VMT) Contraction Benefits of Pooling

High Demand Case example: (low CAV time cost, strong VMT demand response, moderate efficiency).

CAV VMT, PMT, and Energy Use Relative to Manual Vehicle (=1.0)



Relative Energy Use (CAV vs.Non-AV) With Pooling, for Various effects on Route Length

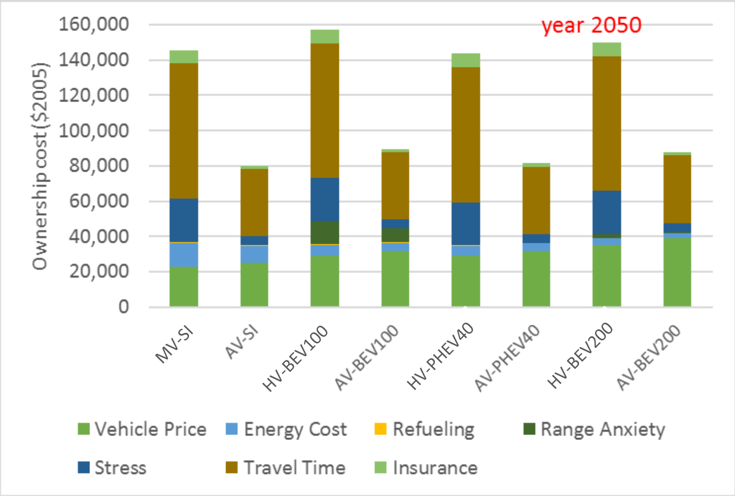


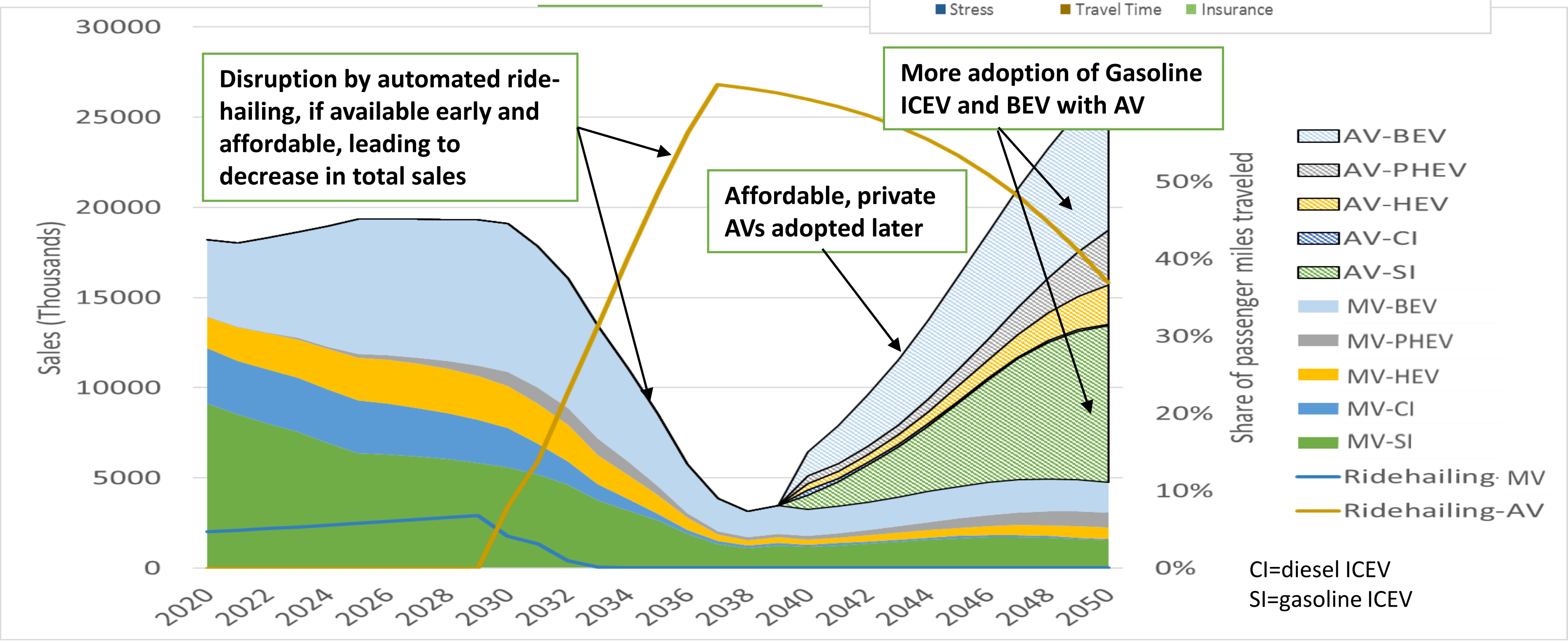
Finding: Pooling can sharply reduce vehicle operation costs/passenger, with some likely increase in passenger time costs. VMT reductions are partially offset by PMT demand response

Accomplishments – Bottom Up

MA³T-MC: Simulating Market Dynamics of Automation and Sharing

- Example scenario: Disruption (decreasing total vehicle sales) with massive adoption of automated ridesharing, then by massive adoption of private AVs (increasing total sales)
- Without AV, total LDV sales would maintain between 16-20 million/year through 2050).
- Providing results to CAVESIM, and to POLARIS/Autonomie tasks





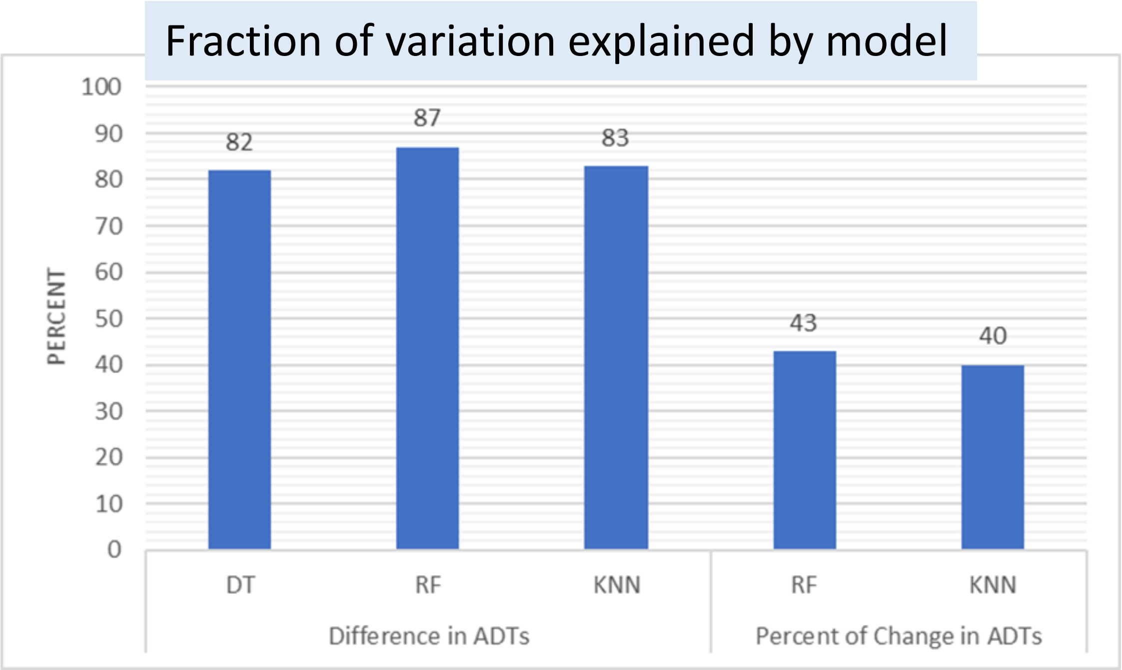
CI=diesel ICEV
SI=gasoline ICEV

Modeling changes in Average Daily Traffic (ADT) flows: Validation

Change or difference between ubiquitous CACC and Base case (no CACC)

- Data mining techniques:
  - – K Nearest Neighbors (KNN)
  - – Decision Tree (DT)
  - – Random Forest (RF)

- Validation of models
  - – Trained models on 70% of data from POLARIS simulations
  - – Evaluated accuracy of models on holdout sample



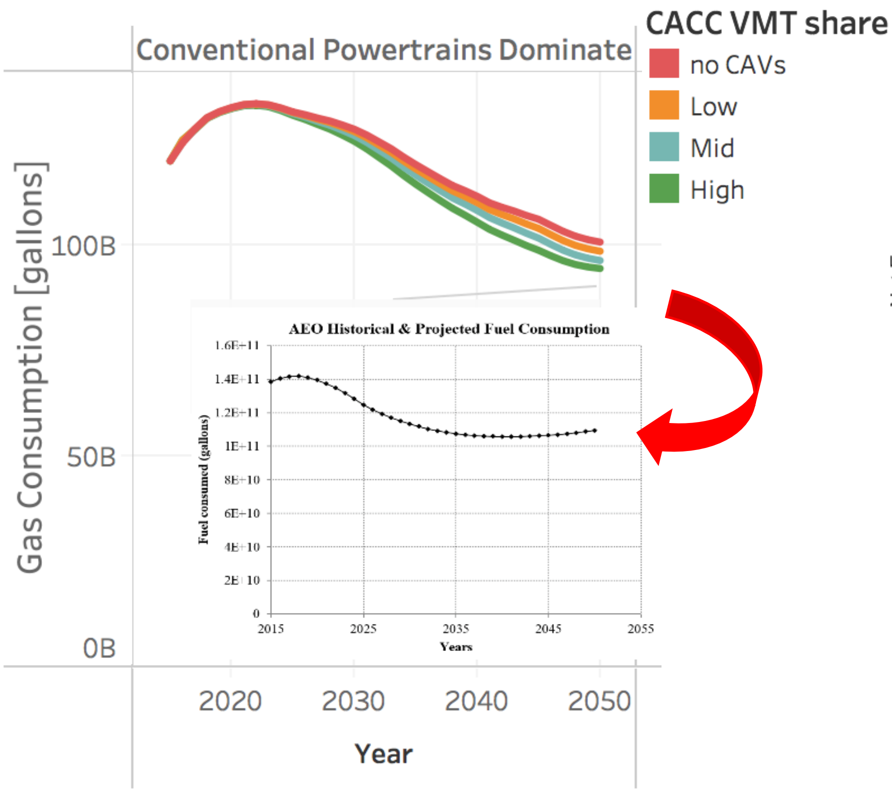
Application at national level requires:

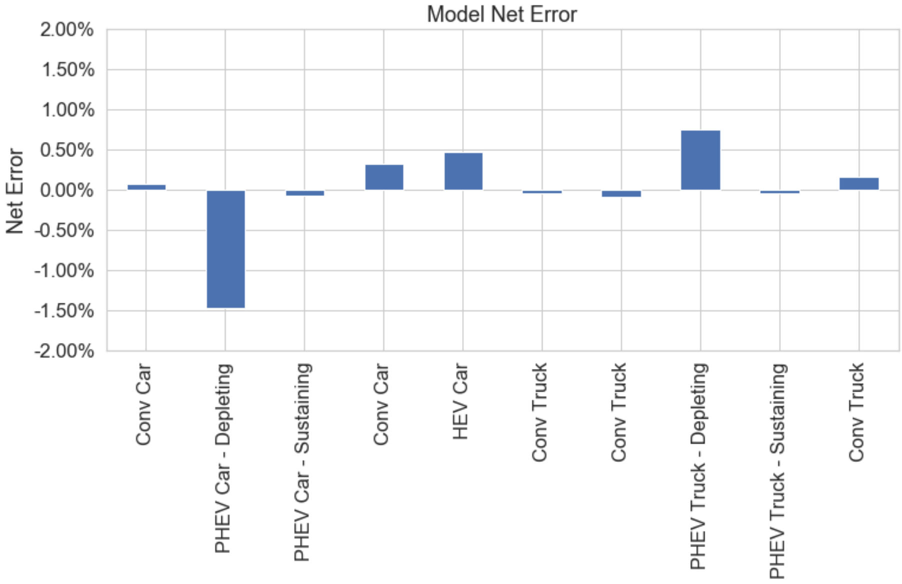
- National dataset for explanatory variables
- Further validation

Fuel Consumption Rate by Driving Condition Roll-Up Approach Validation and Application

- In FY18 national-level approach application compared well with EIA Annual Energy Outlook baseline (while providing flexibility to evaluate various CAVs scenarios)

- In FY19 regional-level version of approach being applied with LBNL to perform energy calculations for the SMART Mobility Workflow scenario runs





Preliminary model iteration shows good agreement with detailed (second-by-second) energy consumption results

Responses to Previous Years Reviewers' Comments

Comment: "… it is important to clarify whether the goal of this project is to generate sound results (less likely) or useful analytical approaches that could be further developed (more likely).."

Response: The intention is **not** to predict the future, but to estimate potential energy and mobility impacts under plausible future conditions and to understand cause-and-effect relationships and to identify factors and conditions that may contribute to desirable energy and mobility outcomes.

Comments: "The transferability analysis seems reasonable but is easy to dispute. The project team should be able to demonstrate how this process provides reasonably accurate answers."

"Focusing more heavily upon further testing and validation of the approach may help build confidence in its validity and applicability."

Response: Through internal checks and validation, it was found that although transferability was demonstrated for travel time and trip rate, but it was not feasible to transfer VMT, however models for traffic flow were validated regionally and may be applicable nationally.

Comments: " … the scope may be too expansive and it may be beneficial to narrow it somewhat."
Response: The project scope has been narrowed to the top-down approach and updating the previous literature synthesis/bounds analysis.

Collaboration and Coordination with Other Institutions

- The three labs (ANL, NREL, ORNL) and the University of Illinois at Chicago and University of Maine are collaborating closely
- Incorporating outputs from additional SMART Mobility performers

Remaining Challenges and Barriers

FY2019:

- Incorporating behavioral research results (from MDS pillar) to CAVs adoption modeling
- Extending top-down CAVESIM models/methods to shared & heavy-duty vehicles
- Analyzing changes in energy, mobility and costs for SMART Mobility Scenarios and contributing to overall program insights on Mobility Energy Productivity impacts
  – Uncertainties in input assumptions in scenarios
  – Uncertainties in functional dependencies (e.g., adoption and travel demand on VoTT, future prices)

Proposed Future Research

FY2019:

- Further refinements to CAVESIM
- Analyzing changes in energy, mobility and costs for SMART Mobility Scenarios:
  - "Sharing is caring" / High-sharing, low-automation
  - "Technology take-over" / High-tech & mobility
  - "All about me" / Low-sharing, high-automation
- Review recent literature and update literature synthesis and bounds (see EEMS081 poster)
- Contribute to overall program insights on Mobility Energy Productivity impacts

FY2020+:

- Explore wider range of scenarios and examine uncertainties
- Analyze scenarios of connectivity and automation in freight movement

Any proposed future work is subject to change based on funding levels

Summary

- DOE (and others) need to understand the potential mobility and energy implications of CAVs at a national level under a range of future conditions
- Costs and values of CAV technologies to travelers are being used to assess potential travel demand and response to price signals (*top-down*)
- Some (interim) findings:
  - National VMT and fuel use vary with full travel costs for connected and automated vehicles (CAVs) compared with manually-controlled vehicles (MVs).
  - Under a range of assumptions about future CAV technology and mileage-based costs of up to $0.20 per mile, CAV VMT outcomes could vary by 25-30%.
  - Mileage costs have greater VMT impact on CAVs than MVs due to their lower overall travel costs and greater travel. (slide 29)
  - Pooling can sharply reduce vehicle operation costs/passenger, with some likely increase in passenger time costs. VMT reductions are partially offset by PMT demand response.
- Adoption projections are available to be used in other SMART Mobility tasks
- Framework developed and exercised for rolling up detailed results for vehicles and travelers (bottom-up)
- Some bottom up methods can expand some regional results to the national level
- Successful models are being used to analyze scenarios of interest

Relevance

Approach

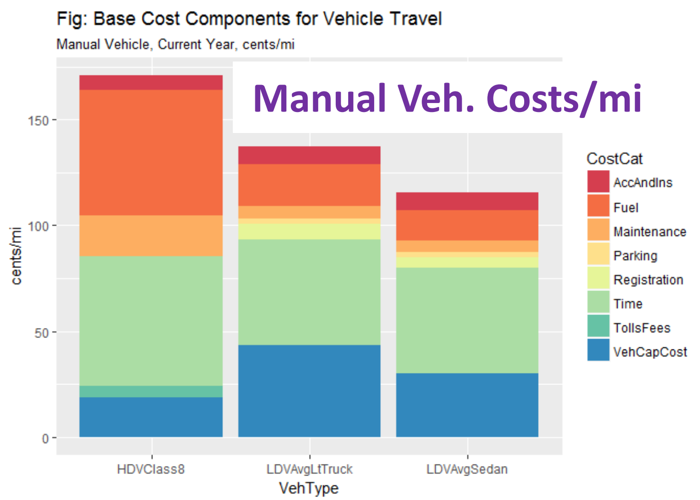
Accomplishments

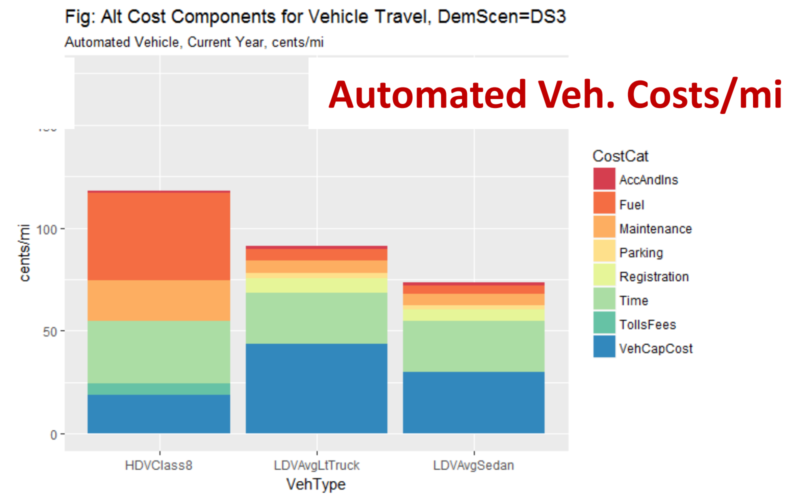
Future work

QUESTIONS?

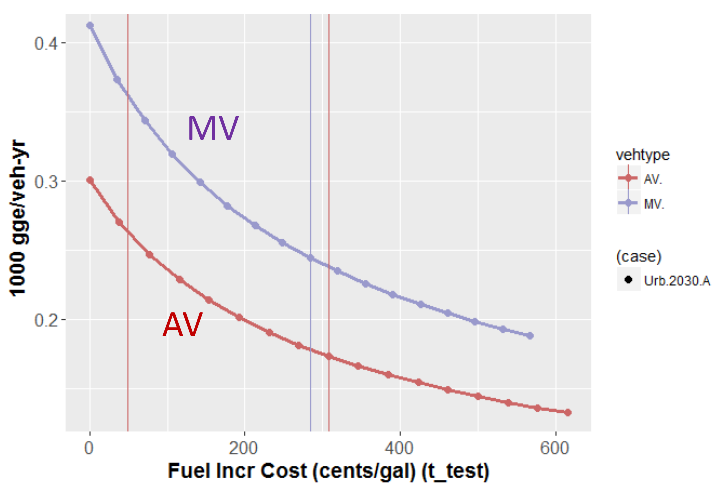
TECHNICAL BACK-UP SLIDES

CAVESIM Results: Economic Costs and the Changes in Strongly Influence Behavior and Outcomes

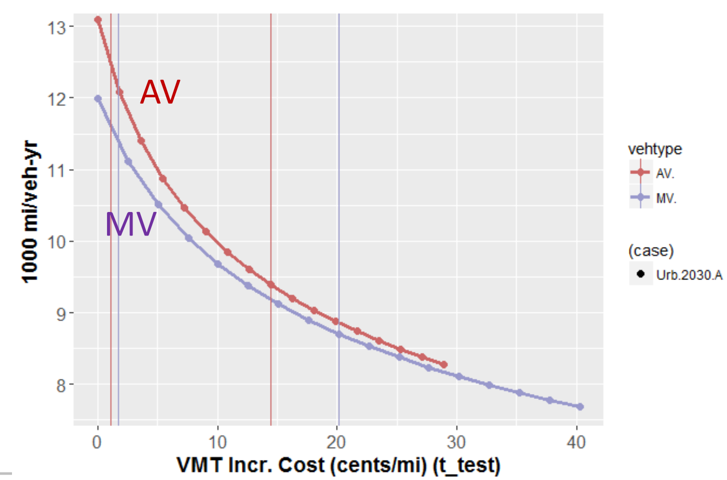




Fuel Use vs. Fuel Incr. Cost



VMT vs. VMT Incr. Cost



Leiby P & J Rubin, 2018, "Efficient Fuel and VMT Fiscal Incentives for Automated Vehicles," Paper 18-04530, presented at the 97th Annual Mtg of the Transportation Research Board, Jan 7-11, Washington, DC.

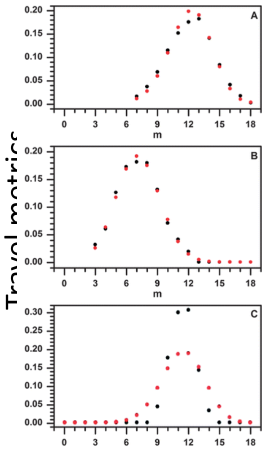
VMT: Use Transferability Modeling to Expand Detailed Travel Simulation Results to The National Level

- **Transfer results from detailed transportation system simulations of CAVs in a metropolitan area to the rest of U.S.**

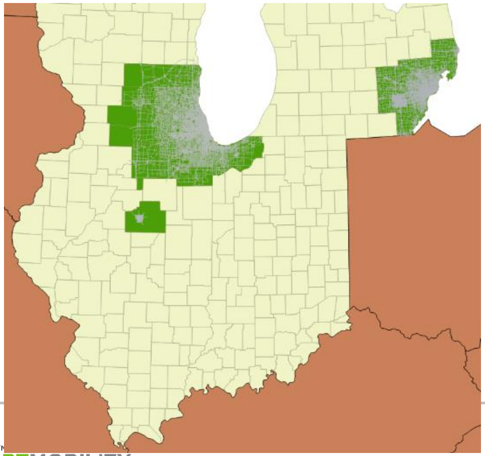
Disaggregated output:
- Socio-demographics
- Land use & built environment
- Activities and travel (trips, VMT)

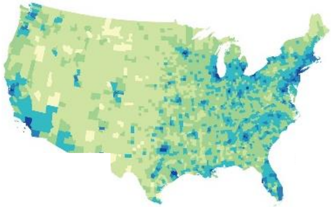
Cluster population by travel patterns

Clusters of travelers

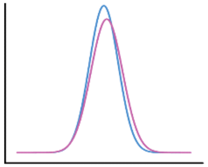


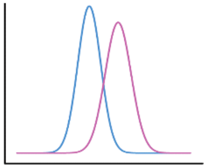
Baseline travel patterns: Activity-based model (POLARIS) of Chicago metro region





Calibrate & update

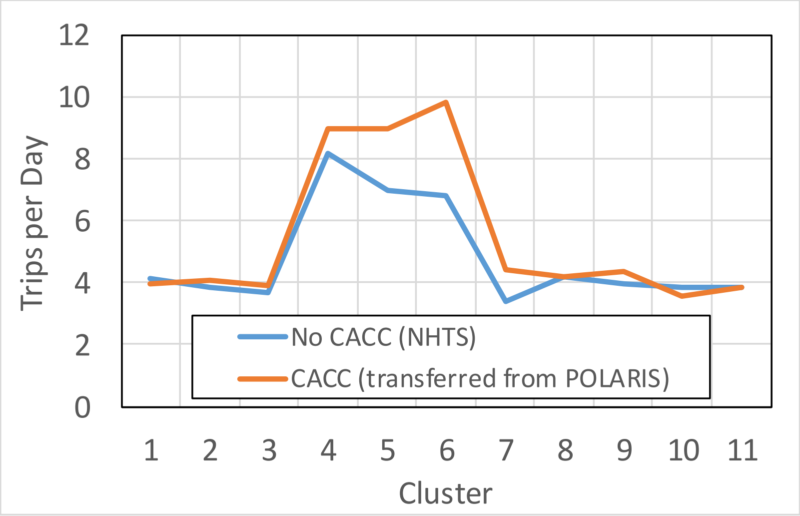


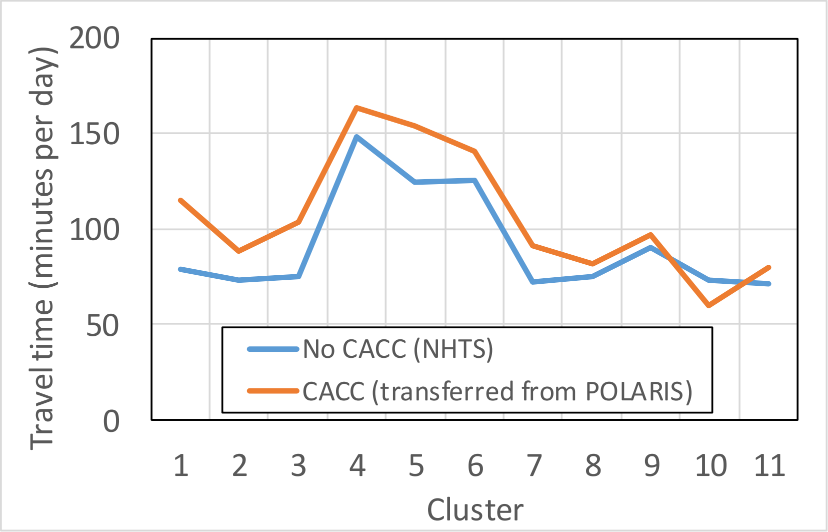


National-level travel patterns:
- Trip rate
- Travel time
- VMT

Travel Time and Trips per Day can be Transferred

- **Two cases, base case (NHTS) and high penetration of cooperative adaptive cruise control (CACC)**
- **With ubiquitous CACC, trip rate and travel time both increase for nearly all population segments (clusters)**



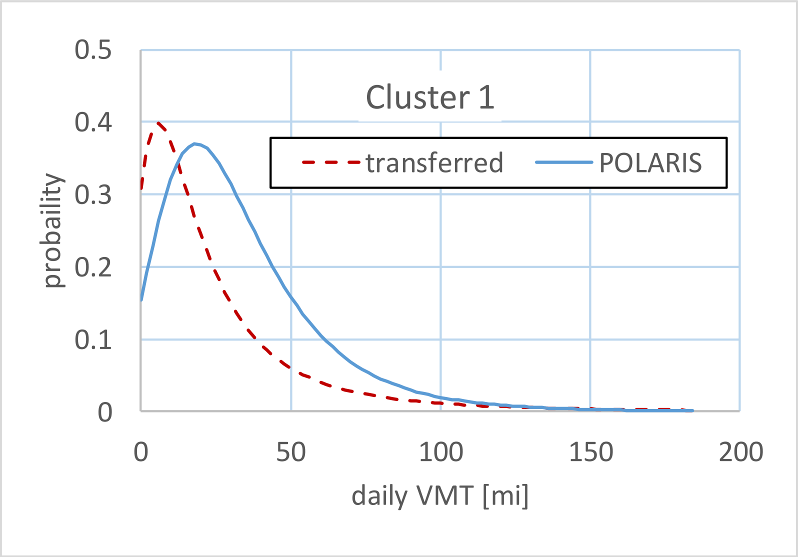


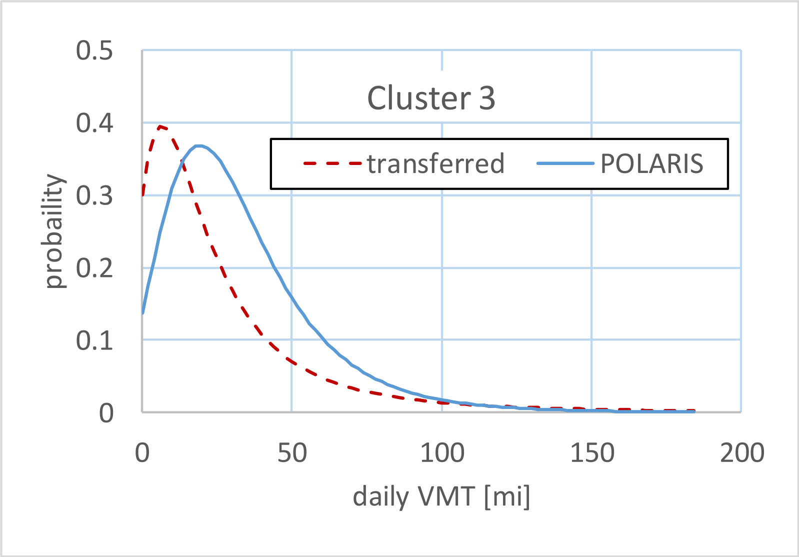
National averages:

	No CACC	CACC
Trip rate	4.66	5.23
Travel time	89	110

VMT not Easy to Transfer by Census Tract

Comparing regional and national distributions – poor match for some clusters





Explanatory power of models is insufficient for reliable transfer of VMT

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